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The aerolayer: airborne filtration by aerodynamic focusing and growth

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Abstract. In this work, a novel approach for airborne filtration with particular reference to medical (non-oil) medical mask is discussed. Here, and contrariwise to current approaches, filtration is attained neither by reducing the hydraulic diameter of the pore nor by increasing the fibre layers thickness-both of them with a strong penalty in the breathability of the mask, but rather by aerodynamic focussing and growth of the particles themselves. Aerodynamic focussing of particles is achieved by a proper simple parallel rearrangement of the traditional crisscrossing fibres-a configuration which we called the aerolayer; and the growth by coalescence. Utilizing a simplified geometrical and physical model, an expression for the required length of the aerolayer was derived. It is shown that the aerolayer is not only able to increase the probability of capture for small particles but also can potentially improve the breathability by reduction of the total thickness of the current layers required. Additional R &D is required in order to arrive to the most optimized practical design of the aerolayer.

Keywords. Airborne filtration; medical masks; COVID-19.

1. Introduction

The world is about to enter its fourth year of living with COVID-19 and although public health authorities are encouraging that 2023 will be a better year than previous ones and the possibility that COVID no longer being a global health emergency in the coming year, however, globally, more than 3 million new cases and 10 000 deaths have been reported in the week of 26 December 2022 to 1 January 2023. Since the beginning of the pandemic several measures have been taken by global governments, such as social distancing, the use of alcohol-based hand sanitizer, or strict enforcement of quarantines. Among all protective measures taken the most conspicuous symbol of the epidemic was/is the use of face medical masks, and, although for asians worn face masks it is a common situation, nevertheless for western countries it has been unusual and yet and after more than two year of pandemic, it is still hardly accepted by population, [1, 2].

Despite that during the first stages of the pandemic, the World Health Organization, and health professionals from different countries claimed that the use of protective masks was not necessary for healthy people, unless they were in contact and/or taking care of people infected with SARS-CoV-2 [3]; the overall perception of effectiveness changed progressively, and their use became recommended and even mandatory in some places. Nonetheless, there is still different opinions regarding the effectiveness of masks to prevent COVID-19 infection. Kwok *et al* [4], for example, states that the effectiveness of face masks is minimal, unless its used accompanied by good hand hygiene, isolation from infected patients and immunization, among other factors, and in the other side, Leung *et al* [5] clearly state the fact that face masks can reduce the transmission of COVID-19 and other influenza viruses. Kähler *et al* [6], found that apart from a FFP3 mask, the rest of the masks used have barely no filtering effect on the droplet sized produced when the subject breathes or speaks. With the start of vaccination campaigns around the world, the opportunity to stop the evolution of the pandemic and its effects arises [7, 8], but until the majority of the world's population is vaccinated, the use of face masks to avoid the spread of the virus is still mandatory.

Understanding the mechanisms through which the virus is transmitted is key in order to avoid the expansion of the pandemic. At this point, it was initially believed that the transport of the virus was mostly due to saliva droplets with 5 to 10 μm-diameter, originated from speaking, coughing, sneezing or just breathing. However, from the second half of 2020, mounting evidence seemed to suggest that transmission could also happen through airborne particles, i.e., particles with diameters ≤ 5 μm [9], and in fact, nowadays, some researchers suggest that it can be the main mechanism of transmission. The problem of airborne transmission is

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due to the fact that, while bigger droplets usually fall to the ground within minutes or less, however, airborne particles not only can travel much longer distances but they can also keep floating in the air for hours in certain conditions [10].

It could be thought, at first glance, that filtering smaller particles will only require either reducing the hydraulic diameter of the pore of the mask by increasing the number of fibre layers. Unfortunately, the solution is not so simple, both aforementioned measures have a big negative impact in the breathability of the mask. Here, and contrariwise to those strategies, a novel concept is proposed, in which filtration is attained neither by decreasing the hydraulic diameter of the pore nor by increasing the thickness or number of crisscrossing layers of the mask, but rather by aerodynamic focussing and growth of the particles themselves.

2. Materials and methods

There are a large variety of masks in the market, but briefly the more important are the -N-95 and KN-95 masks also called respirators N-95s and KN-95s which are designed for a very close facial fit; -Surgical masks also called disposable masks or medical procedure masks which are made of a combination of paper and plastics; -Cloth masks which can be made from a variety of fabrics but unlikely to provide adequate protection against the highly transmissible; and finally -Face shield mask which is not effective from respiratory droplets (they have large gaps below and alongside the face through which droplets can escape). For a comprehensive updated review of the various categories of face masks and current regulations the recent work by Das *et al* (2021) is recommended, [11]. Nevertheless among the different types of masks available in the market, the N-95 type is without doubt the most common of the all the types. The N-95 filters at least 95% of airborne particles but is not resistant to oil-based particles, and therefore, the scope of the present study will be limited to the N-95 (non-oil) type of mask.

2.1 *Assumptions*

The simplifying assumptions valid for a first analytical assessment of the problem are as follows:

- The channels between fibres are represented by its hydraulic diameter, i.e, by an equivalent circular channel
- Laminar flow. The typical values for Reynolds number for medical mask are below 50, and thus the assumption is more than justified
- Airborne particles are spherical
- For preliminary calculations, it is taken the relative velocity between the particle and the flow half of the local fluid velocity as suggested by [12, 13]

To begin with, let us consider a traditional face mask. It is basically formed by a stack of n-vertical layers -generally 3 of them for the case of N95s. Each layer is formed by a bunch of fibres with a random crisscrossing pattern more or less as pictorially sketched at the left side of figure 1. For pressure drop calculations, it is common, the use of hydraulic diameter d_h, in which the voids or empty spaces between the fibres are represented by the equivalent round tube or channel which gives similar hydraulic calculations. With the use of the hydraulic diameter, a Reynolds number **Re** of the equivalent channel may be defined as

$$\mathbf{Re} = \frac{2\bar{v}_f r_h}{\nu} \tag{1}$$

where $\bar{v}_f$ is the mean air velocity; $r_h = \frac{d_h}{2}$ is the hydraulic radius; and ν is the kinematic viscosity of the fluid. Taking into account that typical breathing velocities vary from 1 m/s to 10 m/s, or thereabouts, [15], and considering a value for the kinematic viscosity of air $\nu = 1.5 \times 10^{-5}$ m^2/s at 20°C, with a hydraulic diameter of the pore for a medical mask in the range between 50 to 60 µm, [14], it is easy to see that the Reynolds number falls in the laminar regime with values less than $\mathbf{Re} \approx 30$, and thus it is allowable to use the well known Hagen-Poiseuille equation for the estimation of the pressure drop through the equivalent channel which is given by

$$\Delta p = \frac{8\rho\nu L\bar{v}_f}{r_h^2} \tag{2}$$

where L is the length of the channel. Thus, in order to prevent the leakage of a given particle through the layer, current filtration strategies can recourse either in a decrease of the diameter of the pore or in increasing the length of the equivalent channel i.e., its thickness. It is easy to see, from

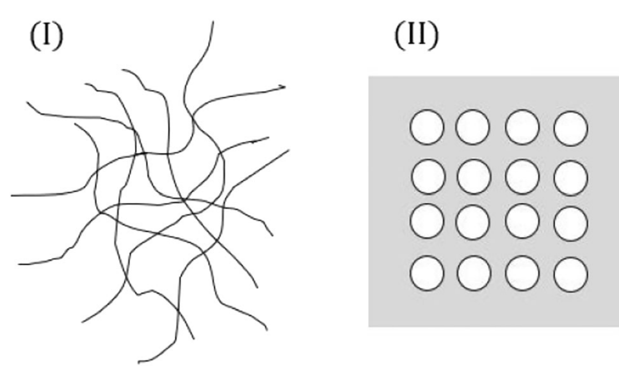

Figure 1. (*I*) Schematic of the crisscrossing fibres layer in a face mask (*II*). Equivalent mask layer model using the hydraulic diameter.

Eq. (2) the detrimental effect on the pressure drop -and then on the breathability of the mask, if reduction of the pore is performed, and for the increase of the length i.e., the thickness of the layer or the number of layers, although to a minor extent, however, also with a direct impact in the breathability of the mask.

2.2 *The aerolayer*

Let us assume a medical mask which is composed by the traditional inner, middle and outer fibre layers as pictorially depicted in figure 2 at the left side. Now, let us replace the middle crisscrossing layer by a parallel rearrangement of the same fibres in the direction of the flow as shown in the same figure 2 at the right side. Because this new arrangement-hereafter called as the *aerolayer*, a virtual channel is created and then a velocity and pressure gradient developed because the condition of zero slip at the walls of the fibres. Thus, when a new particle enters, the *aerolayer* will experience a pressure gradient field surrounding it which translates into a lift force which will push the particle towards the center of the channel, i.e., acting as a focusing force. Once the particle arrives at the centerline it will meet other particles already focused and upon contact coalesce will occur creating a single big droplet which now can be easily captured by a crisscrossing fiber sheet just in front of the *aerolayer*.

To asses the feasibility of the above mentioned concept, the most critical parameter is the determination of the length of the *aerolayer* required in order to focus the particles before they are exiting the channel. In order to develop the theoretical treatment in the next analysis, the actual shape of the channel, and the physical model used are shown in figure 3. Taking into account the laminar regime, the flow profile may be approximated by a parabolic Hagen-Poiseuille profile which for a fully developed flow at a given radial position r from the centerline of the channel is given by

$$v_f(r) = 2\bar{v}_f\left[1 - \frac{r^2}{r_h^2}\right] \tag{3}$$

where $v_f(r)$ is the axial fluid velocity at a given position r from the centerline; and $r_h = \frac{d_h}{2}$ is the hydraulic radius of the channel. Saffman (1965) [16], derived an expression for the lift force F_l acting on spherical bubbles at laminar regime under the presence of a velocity gradient, and a modified equation was presented by Mei and Klausner (1994) [17]

$$F_l = \frac{1}{2}c_l\rho v_r^2\pi a^2 \tag{4}$$

where c_l is the lift coefficient, v_r is the relative velocity between the fluid and the droplet and a is the bubble or droplet's radius. In regard to the relative velocity v_r, no model for the bubble sliding velocity exists in the literature, [12], but in view of the several uncertainties in the analysis we assume a bubble sliding velocity half of the local fluid, i.e., $v_b = 0.5v_f$ as suggested by [12] and [13], which seems

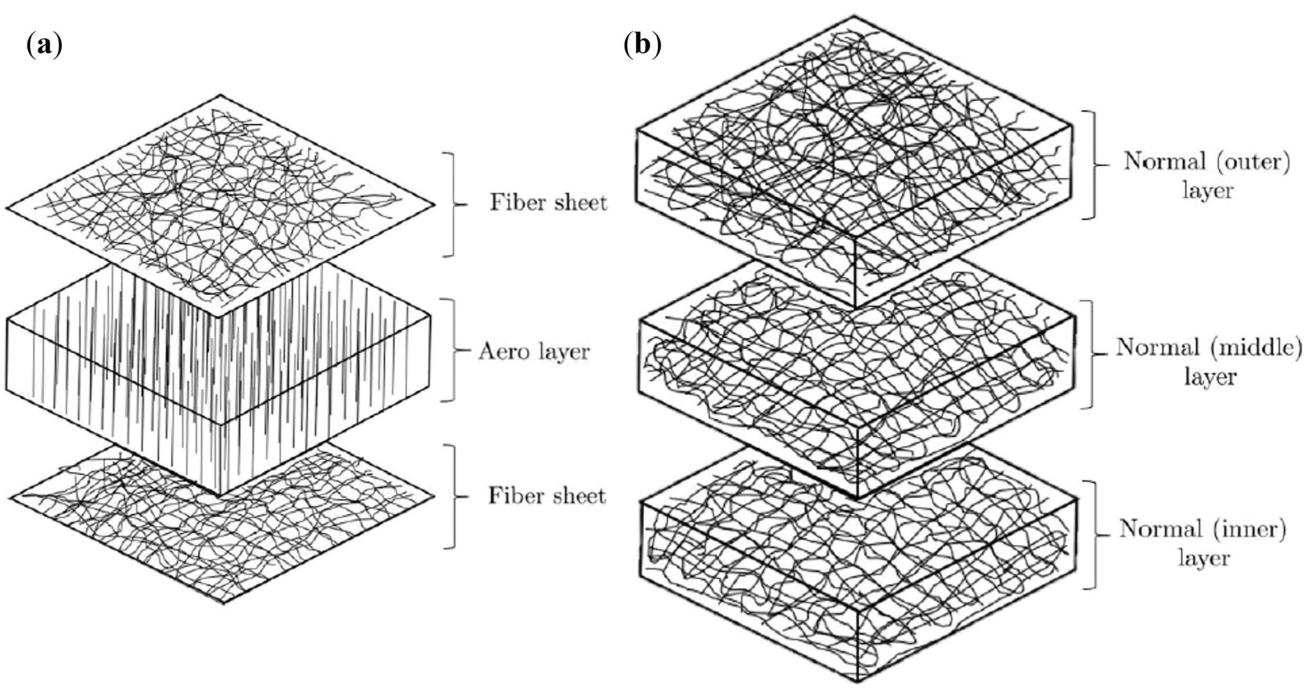

Figure 2. Sketch of the core idea. (a) left side: typical crisscrossing fibres layers used in traditional face masks; and (b) right side: the use of the proposed aerolayer.

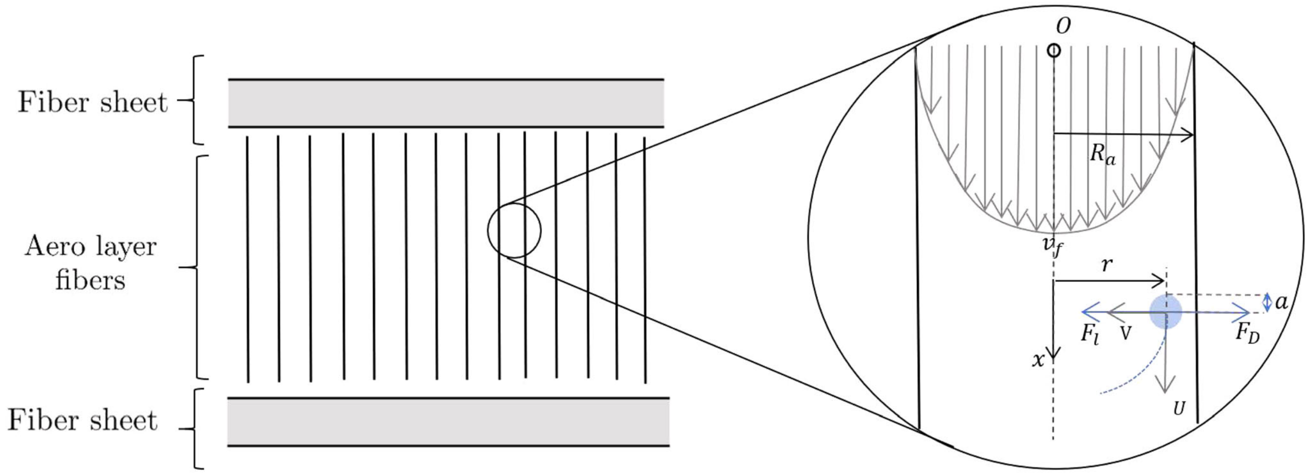

Figure 3. Cross section of the proposed stack of fibre layers and forces experienced by a droplet inside the "aerolayer".

that is the best figure which agrees well with the predictions by those authors in the calculation of the lift. For small Reynolds numbers, the lift coefficient is simplified as [12]:

$$c_l \approx 2.74 \frac{dv_f}{dr} \frac{\nu^{1/2}}{v_r} \left(\left| \frac{dv_f}{dr} \right| \right)^{-\frac{1}{2}} \tag{5}$$

where $\frac{dv_f}{dr}$ is the radial velocity gradient which can already be calculated from Eq. (3). On the other hand, because the radial motion induced by the lift forces, a drag force is also developed, which opposes the lift force. This drag force on a laminar regime is given by [18]:

$$F_d = -4a\pi\rho\nu u_b \tag{6}$$

where u_b is the transverse (radial) bubble velocity. Assuming uniform, creeping motion in the r-direction, both forces are balanced

$$F_d = -F_l \tag{7}$$

Taking into account Eqs. (4)–(6), one obtains for the transverse bubble velocity the following relationship

$$u_b = -0.685 \frac{\bar{v}_f^{\frac{3}{2}}}{\nu^{\frac{1}{2}}} \frac{a}{r_h} \left[1 - \frac{r^2}{r_h^2} \right] r^{\frac{1}{2}} \tag{8}$$

Now, the calculation of the length of the aerolayer is straightforward. For any infinitesimal radial displacement dr, the corresponding infinitesimal interval of time dt, is given by

$$dt = \frac{dr}{u_b} \tag{9}$$

and thus the corresponding axial infinitesimal displacement dx is given by multiplying the interval of time dt by the axial velocity of the bubble v_b at that point

$$dx = v_b dt \tag{10}$$

where the axial velocity of the bubble can be calculated from the relative velocity as $v_b = v_f - v_r$ which considering the already mentioned approximation $v_r = 0.5v_f$ yields $v_b = 0.5v_f$, and thus Eq. (10) becomes

$$dx = 0.5v_f dt \tag{11}$$

Taking into account Eq. (3), Eq. (8) and Eq. (9) inserted into Eq. (10), we obtain for the magnitude of dx

$$dx = -1.46 \sqrt{\frac{\nu}{\bar{v}_f}} \frac{r_h}{a} \cdot \frac{dr}{r^{\frac{1}{2}}} \tag{12}$$

If we assume the worst hypothetical case, i.e., when the bubble of radius a is initially at the most distant position from the centerline $r = r_h$–a-which maximizes the length of the aerolayer required, and as final position $r = a$, then the length of aerolayer is given by

$$\int_0^L dx = -1.46 \sqrt{\frac{\nu}{\bar{v}_f}} \frac{r_h}{a} \int_{r_h - a}^{a} \frac{dr}{r^{\frac{1}{2}}} \tag{13}$$

which upon integration yields

$$\frac{L}{r_h} \simeq 2.92 \sqrt{\frac{\nu}{\bar{v}_f}} \frac{1}{a^{\frac{1}{2}}} \left[\left(\frac{r_h}{a} - 1 \right)^{\frac{1}{2}} - 1 \right] \tag{14}$$

and when the particles are very small in comparison with the channel is simplified as

$$\frac{L}{r_h} \simeq \frac{4.13}{\sqrt{\mathbf{Re}}} \frac{r_h}{a} \tag{15}$$

The above equation is consistent regarding what is known on lift forces acting on channels, where it is known that the lift force is proportional to the ratio $\frac{r_h}{a}$. Thus, force decreases as the ratio increases and then the required length for focusing the particles increases. Finally, although the present work is a first assessment on the concept, and therefore the optimization of the *aerolayer* is out of scope of this preliminary work, it is easy to see by looking at Eq. (15) that the *aerolayer* offers interesting additional possibilities. For example, increasing the radius of the channel r_h will increase the required length for aerodynamic focusing, however, in addition, by increasing the hydraulic radius, will have a direct improvement in the breathability of the mask (see Eq. (2)), and thus, there will be a compromise between the length and the breathability. Because the aerolayer even using the same hydraulic diameter than the traditional mask has a reduction of the total thickness of the mask by replacing the inner and outer thick crisscrossing layers by two thin sheets (see figure 2), then if it is kept the same thickness of the mask, the aerolayer can use larger hydraulic diameters and thus improving the breathability further.

3. Results

In order to obtain an idea of the required length of the aerolayer for aerodynamic focusing of the particles we assume a kinematic viscosity of air of $\nu = 1.5 \times 10^{-5}$ m^2/s at 20 °C. The resulting curves for several radius of the droplets as a function of the mean breathability velocity are shown in figure 4. It is seen that the length of the aerolayer is below 1 mm, so even considering the several uncertainties in the model, it seems that the aerolayer will be in any case a few millimeters as much. As a result, the substitution of the inner and the outer thick layers by the aerolayer not only will result in a capability to capture the airborne particles (by aerodynamic focussing and growth)

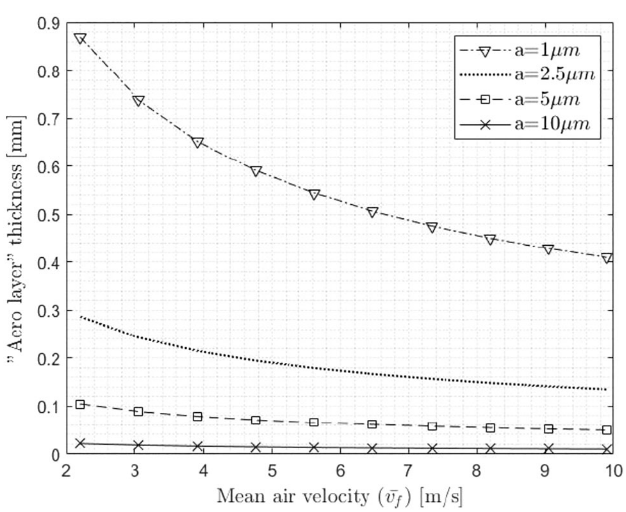

Figure 4. Required length of the *aerolayer* as a function of the mean air velocity for different droplet radius.

but actually because the aerolayer has approximately the same thickness of a single layer from a convectional mask but the other two layers (top and bottom) are not required as is the case for the traditional masks (see illustrative comparison in figure 2) because in the aero layer concept, the top and bottom are not layers but just fibre sheets whose purpose is holding the aerolayer and then it translates into a reduction of the thickness $\simeq \frac{2}{3}$ of that used in the traditional approach.

3.1 *Coalescence and growth*

Now we have next to turn our attention to what happens once aerodynamic focusing occurs. In the preceding section, it was discussed that by a proper parallel rearrangement of the fibres, an aerodynamic focusing effect is induced. An expression was derived, Eq. (14), for the estimation of the required length of the channel (the length of the fibre) in order to attain the desired aerodynamic focussing effect showing that the concept has merit to be further considered.

However, the aerodynamic focussing induced by the aerolayer only promotes the clustering of particles at the center of the channel but does not guarantee, per se, that particles will “melt” into bigger particles, i.e., that coalescence actually happen, which, as a matter of fact is the real objective pursued with the concept. Indeed, upon the contact of particles induced by the *aerolayer*, the particles can actually: a) rebound; b) breakup apart and then obtaining an effect diametrally opposite, i.e., generating from a big particle several smaller particles which clearly is worsening the situation for filtration; or c) they can coalesce into a bigger particle which is the desired effect. These situations are pictorially sketched in figure 5. Therefore, it is mandatory to asses what kind of process is predominant, i.e., the rebound, the breakup or coalescence. The dominant mechanism can be assessed by the the probability of coalescence. Many models for the estimation of this probability are available in the literature, for example, models based in a balance of energies, [19], but in view of uncertainties, the simplest model based on the relative velocities of collision given by Liao *et al* [20], seems preferable. According to this model, the probability, λ, that two droplets coalesce into one bigger droplet is based on the relative velocity between them at the moment of collision and on a certain critical velocity term, 20]

$$\lambda = min\left(\frac{v_{crit}}{v_c}, 1\right), \quad with \quad v_{crit} = \sqrt{\frac{0.03\gamma}{\rho_c r_{eq}}} \tag{16}$$

where v_{crit} is the critical velocity of the droplets; v_c is the relative velocity of collision; γ is the surface tension of the bubbles; ρ_c is the droplet’s density; and r_{eq} is the equivalent droplet radius defined by

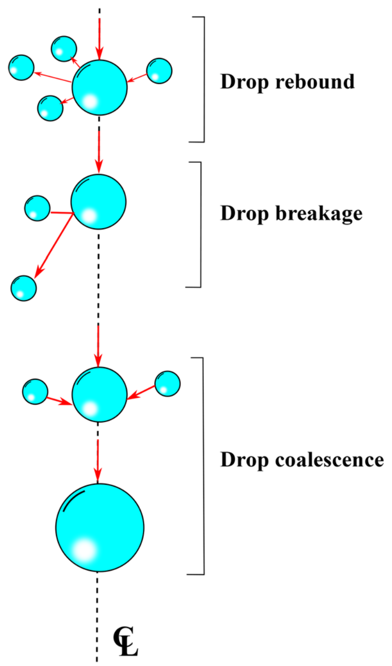

Figure 5. Upon contact, induced by the focusing effect of the *aerolayer*, drops can rebound, break into small ones or grow by coalescence.

$$r_{eq} = \frac{2a_1a_2}{a_1 + a_2} \tag{17}$$

being a_1 and a_2 are the radius of the droplets. It is clear that a myriad of collisions with different angles and different velocities in direction and magnitudes are permissible, Nevertheless, for preliminary estimations, the most pessimist case must be considered, i.e, considering the maximum velocity of collision which minimizes the probability of coalescence according with Eq. (16).

Let us assume two droplets of radius a_1 and a_2, one of them, say, the droplet with radius a_1, already focused in the centerline, and other with radius a_2 which is approaching as sketched in figure 6. The particle a_1 in the centerline has only axial motion (a stability point where no radial forces exist), and, on the other hand, the particle with radius a_2 has two motions, namely, the axial and the radial motion (due to the lift which is propelling the particle toward the centerline). However, because the radial velocity is orders of magnitude lower than the axial velocity, we can neglect in our reasoning the radial motion in comparison with the axial velocity for the calculation of the collision velocity. It is seen, that the maximum velocity of collision between both particles is approximated as the relative axial velocity between particles separated each other a distance $a_1 + a_2$. With the above assumption, if particle of radius a_1 is already in the centerline and that with radius a_2 is approaching, from Eq. (3) one obtains the most pessimistic collision velocity as

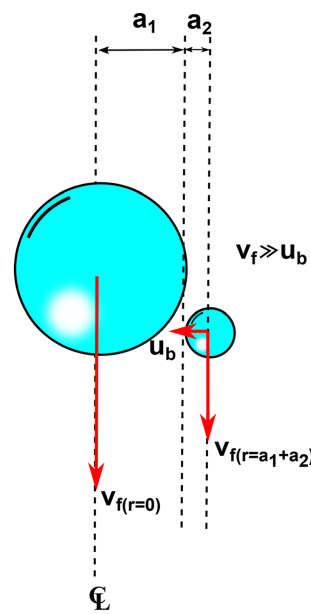

Figure 6. Physical collision at the centerline between droplets.

$$v_c \simeq \bar{v}_f \left[\frac{(a_1 + a_2)^2}{r_h^2} \right] \tag{18}$$

4. Discussion

In order to obtain an idea of the probability of coalesce for several radius of water droplets, it was computed the relationship Eq. (16) for bubble's radius ranging from 0.5 to 10 µm, and four typical values of the mean breathing velocity of 2.5, 5.0, 7.5 and 10.0 m/s. The density of the water as well as its surface tension were taken as $\rho_{pc} = 1000$ kg/m^3 and $\gamma = 72.8 \times 10^{-3}$ N/m at 20 °C, respectively. The resulting curves are shown in figure 7. It is seen that coalescence for small airborne particles is always 1, even for improbable high velocities as 10 m/s. Only for big particles the probability drops to 0.8 or thereabouts, but for this case, there is not need for coalesce because they can easily trapped by the traditional crisscrossing fibre layer. Finally, the feasibility for industrial manufacturing the aerolayer must be addressed in future research, however, the technology for fiber alignment is already a relatively mature technology, [21] and several technological approaches are available being alignment by electrospinning one of the most used, [22, 23] allowing not only fiber alignment but also setting tensile properties and other specific applications from the designer.

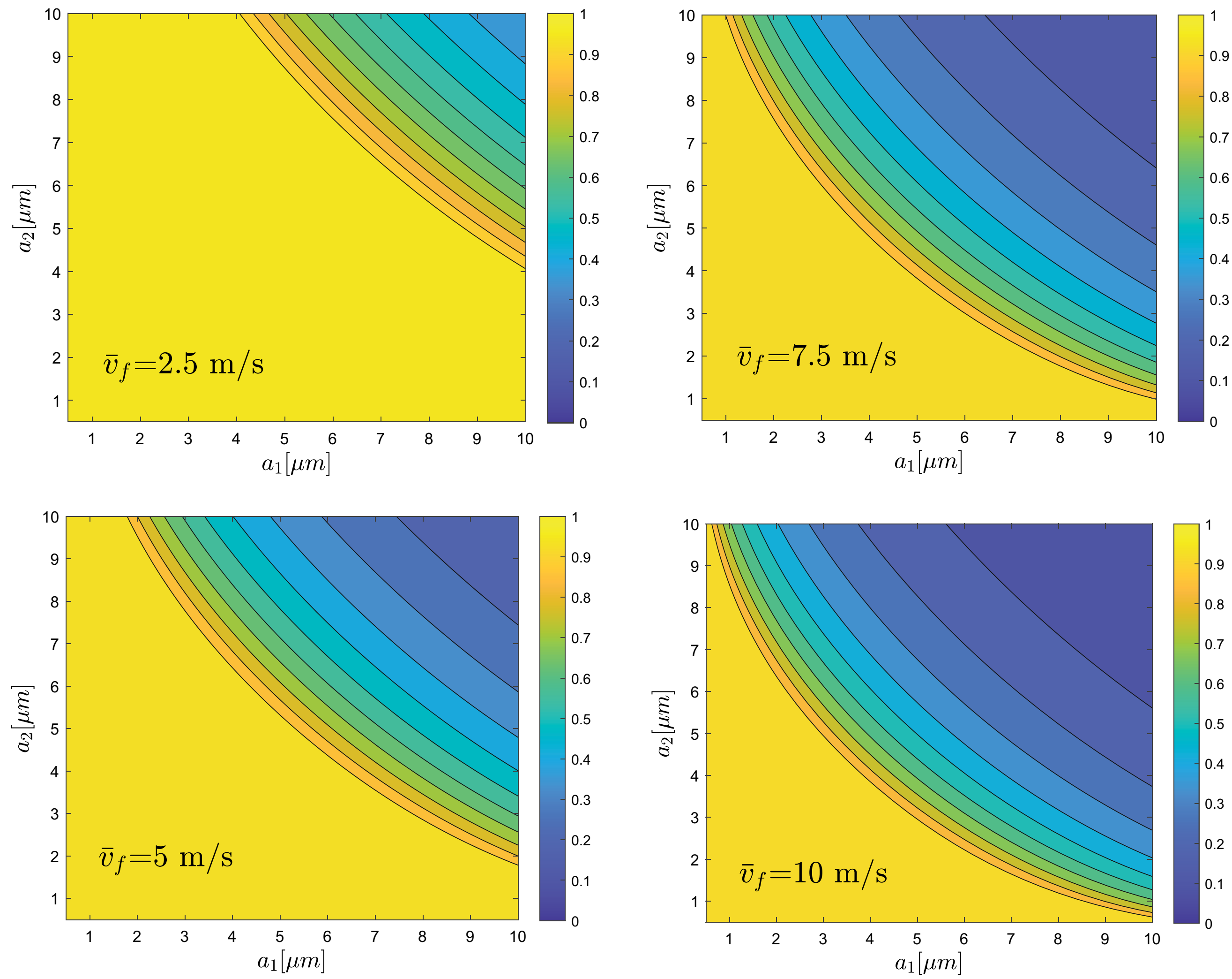

Figure 7. Water droplets coalescence probability for several values of the mean velocity of the fluid.

5. Conclusion

In this work a novel approach for airborne filtration and with particular reference to medical mask was discussed. In this concept, and contrariwise to current approaches, filtration is attained neither by decreasing the equivalent diameter of the pore nor by increasing the thickness or number of fibre crisscrossing layers-both of them with a strong penalty in the breathability of the mask, but rather by aerodynamic focussing and growth of the particles themselves. Aerodynamic focussing of particles is achieved by a simple proper parallel rearrangement of the crisscrossing fibres which was called the aerolayer, and once focalized upon contact, growth of particles occurs by coalescence, which for typical breathing velocities and interesting sizes of particles has a probability near to 1. Additional R &D is required in order to arrive at the most optimized practical design of the *aerolayer*.

List of symbols

a	Droplet's radius
c_l	Lift coefficient
d_{eq}	Droplets equivalent diameter
d_h	Hydraulic diameter of the channel
F_d	Droplet's drag force
F_l	Droplet's lift force
L	Thickness of the mask layer
p	Presssure
r	Radial position, coordinate
r_h	Hydraulic radius of the channel
Re	Reynolds number of the channel
t	Time
u_b	Velocity of the droplet in the radial position
v_b	Velocity of the droplet in the axial direction
v_c	Relative-collision velocity between droplets
v_f	Air velocity
$\bar{v_f}$	Mean air velocity
v_{crit}	Droplet critical velocity

v_r Relative velocity between the air and the droplet
x Length co-ordinate

Greek symbols
λ Probability of coalesce
v Kinematic viscosity of air
μ Dynamic viscosity of air
ρ Air density
γ Surface tension
ρ_c Water density
λ Coalescence probability

Subscripts
b Bubble
c Collision
d Drag
h Hydraulic
l Lift
f Fluid
r Relative

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